

# MONTE CARLO RADIATION ANALYSIS OF A SPACECRAFT RADIOISOTOPE POWER SYSTEM

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## ABSTRACT

A Monte Carlo statistical computer analysis was used to create neutron and photon radiation predictions for the General Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS RTG). The GPHS RTG is being used on several NASA planetary missions. Analytical results were validated using measured health physics data.

## 1. INTRODUCTION

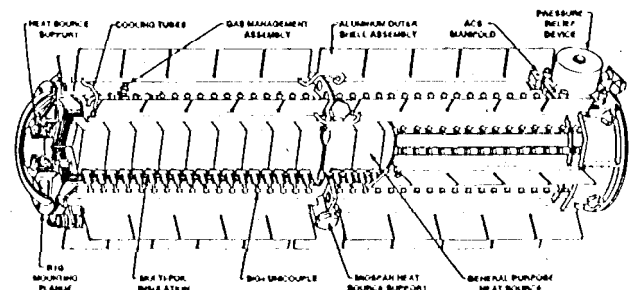
In late 1997, engineers at NASA's Jet Propulsion Laboratory are planning to launch a robotic spacecraft on an eleven year mission of over one billion miles to Saturn and its moon Titan. Like the other four outer planets (Jupiter, Uranus, Neptune, and Pluto), Saturn orbits too far from the sun to be explored by spacecraft using the solar arrays currently available. To date, spacecraft sent to study and photograph these planets have required Radioisotope Thermoelectric Generators (RTGs) to meet electrical power requirements.

### A. Description of the GPHS RTG

RTGs are built for NASA by the Department of Energy under an interagency Memorandum of Understanding. The SNAP series and Multihundred Watt RTG models were used on spacecraft in the 1960s and 70s. Figure 1 shows a cut away of the General Purpose Heat Source (GPHS) RTG currently in production. The GPHS RTG is already powering both the Galileo mission now on its way to Jupiter and the European Space Agency's Ulysses mission studying the polar regions of the sun. The 1997 Cassini mission to Saturn will use three of the GPHS RTGs.

The GPHS RTG is fueled by  $^{238}\text{Pu}$  in the form of iridium-clad  $\text{PuO}_2$  fuel pellets. Four of the pellets are encased in a single graphite module. Fifteen modules are

Figure 1  
GPHS RTG



then stacked together inside in the cylindrical thermoelectric converter. The exterior of the converter is a finned aluminum shell that supports the GPHS modules on either end of the stack. Multifoil insulation inside the case retains the heat generated by the radioisotope fuel decay. The shell supports 572 silicon germanium thermoelectric unicouples that penetrate through the insulation. The temperature differential across the uncouple creates an electrical potential, that in conjunction with the other uncouples generates several hundred watts of power.

### B. Spacecraft Radiation Considerations

While the static conversion and long fuel life of RTGs make them dependable space power sources, the neutron and photon radiation from the fuel can affect equipment reliability and create personnel hazards. Ionizing dose from high energy gamma and neutron displacement effects can damage spacecraft electronics. Low energy and secondary photons can degrade the return from sensitive science instruments. And at the launch facility, personnel exposure risks near the RTGs can complicate spacecraft integration and testing operations.

## 11. RADIATION ANALYSIS

Various empirical, deterministic, statistical, and hybrid techniques have been used in the past in an effort to closely characterize the radiation from RTGs. Most recently, the GPIIS RTG design was modelled using the Los Alamos Monte Carlo code MCNP4<sup>1</sup> on both a CRAY Y-MP and an IBM 486 PC.

### A. Description of the MCNP4 Computer Code

Beginning from a user defined source, MCNP4 statistically simulates transport of a series of individual particles (neutrons, photons, or electrons) through a computer modelled geometry. The contributions from the particles are tallied at a point, over a surface, or in a user designated volume. When enough particles or histories are tracked, a representative value is attained for that particular tally. Particle energy, direction, event cross-sections, and other continuous and discrete distributions are stochastically sampled using Monte Carlo techniques. Numerous non-analog variance reduction and modelling options are available.

### B. RTG Model Geometry and Source Spectrum

Most of the GPIIS RTG geometry was modelled in detail, making extensive use of the MCNP4 repeated structure features. In the interest of simplicity and reduced run-time, however, the approximately one hundred layers of insulation and the 572 thermoelectric unicouples were lumped into two cells of homogeneously distributed representative elements. The validity of this simplification was demonstrated through independent runs that confirmed the relatively small importance of these low density components over the full neutron and photons spectrum.

Little of the spacecraft was included in the problem geometry. During worst case conditions when the fuel tanks are empty, there are few components that would effectively shield high energy gamma and neutrons. However, local shielding used to protect the sensitive spacecraft cameras was evaluated to help determine the spectrum and flux density of X-rays reaching the camera CCDs.

The fuel source spectrum was initially based on previous analyses of the PuO<sub>2</sub> fuel.<sup>2,3</sup> That work was then updated to account for differences in fuel age, 111-236 impurity concentrations, monatomic Oxygen-18 content, and light element impurity levels - all of which significantly impact either photon or neutron source levels. The defined source spectral breakdown is shown in Figures 2 and 3.

Figure 2  
RTG Neutron Source Spectrum

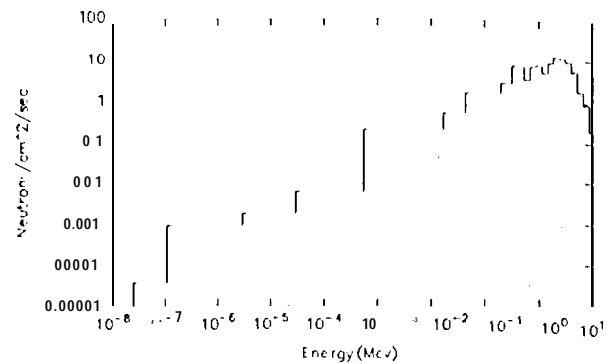
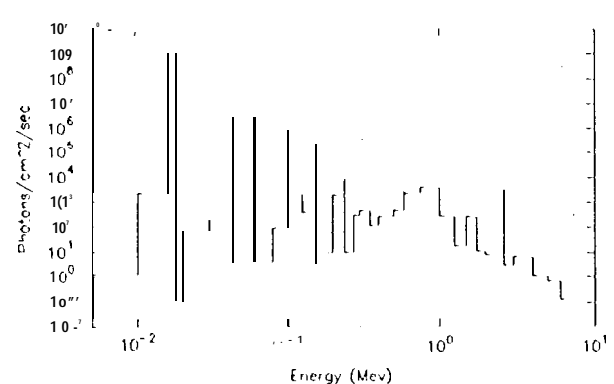


Figure 3  
RTG Photon Source Spectrum



### C. Analysis Technique

A determined effort was made to ensure that the problem phase space was well sampled. Of particular concern, due to the sensitive science instruments, was the low energy photon spectrum. Photon transport was done using the MCNP detailed physics treatment that included pair production, photoelectric fluorescent emissions, Compton and Thomson scattering down to 0.001 MeV. Estimates of X-ray generation in the thick shielding for the spacecraft camera CCDs required bremsstrahlung approximations as well. No thermal neutron transport was modelled, however fast neutron fission in the fuel was included.

Several variance reduction features were used during the analysis to minimize run-time and improve the accuracy of the model. Source biasing allowed all energy bins in the source to be sampled frequently enough that the characteristics of photons at all energy levels of interest were well understood. Implicit capture, allowed statistically captured particles, to continue making weighted contributions to detector tallies. Accurate analysis of the thick CCD shielding required an energy splitting game to

be used for 1-10 Kev photons. Finally, the forced collision option proved very helpful in verifying infrequent events in much of the lower density material.

1 Due to the potentially broad spectral response of several science instruments carried on board the spacecraft, many variance reduction options were purposely avoided where practical to help preclude data loss in the tail of the energy spectrum. Particle weight windows, energy cut-off, and statistical roulette games in general were not used.

### III. RESULTS

#### A. Statistical Characteristics

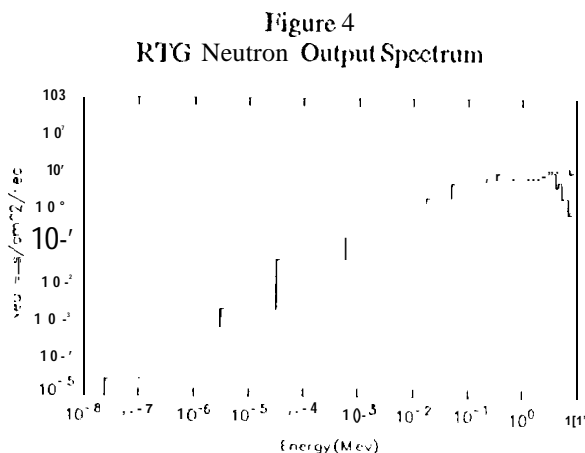
The statistical precision of the final RTG model detector tallies was good. Most energy bins converged to a relative error of  $R \leq 0.05$  within 100,000 histories, where:

$$R = \frac{S_x}{\bar{x}}, \quad S_x = \text{std dev} \\ \bar{x} = \text{mean}$$

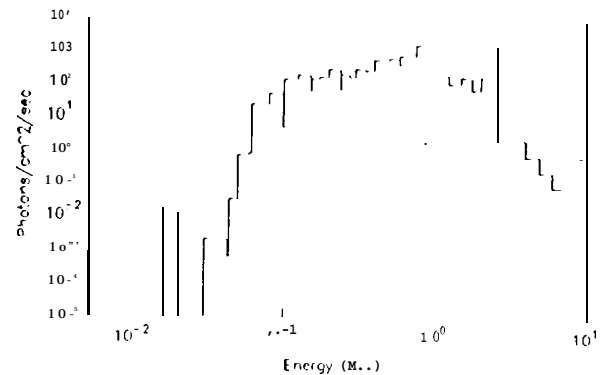
All tallies were well behaved with little fluctuation in detector statistics. Relatively rapid convergence allowed single points to be evaluated with sufficient accuracy within reasonable computer run times. Overnight runs on the CRAY system and the PC were used to calculate levels at hundreds of points for two dimensional contour plots.

#### B. Comparison of Predicted and Measured Data

Figures 4 and 5 show the spectral outputs from the runs. No measured data was available for  $\text{PuO}_2$  RTGs to verify the spectral analysis.

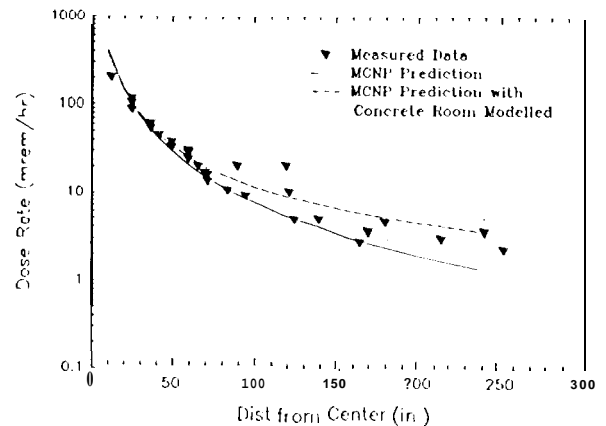


**Figure 5**  
**RTG Photon Output Spectrum**

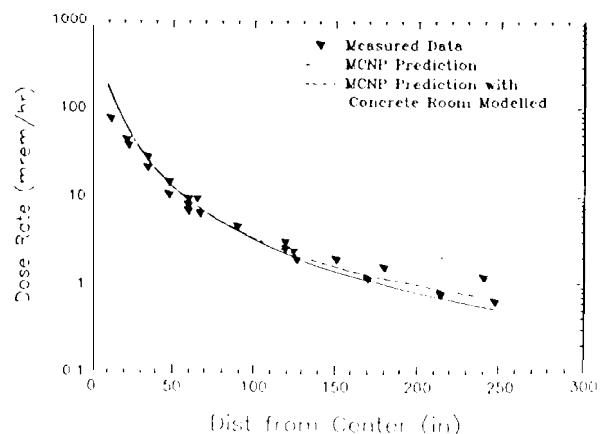


MCNP dose rate results compared well with RTG health physics data. Figures 6 and 7 compare predicted radiation levels radially out from the RTG centerline to measured data in the same locations.

**Figure 6**  
**Neutron Dose Rate Predictions vs. Measured Data**

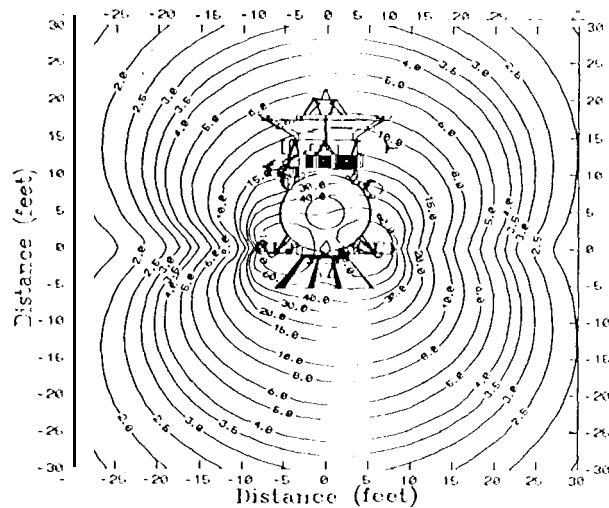


**Figure 7**  
**Photon Dose Rate Predictions vs. Measured Data**



All measurements were normalized to a fuelage of 5 years. Since most of the empirical data was collected in a relatively small concrete storage room, a second MCNP prediction was performed that included a generic 2.0x30x15 foot concrete room in the model to account for backscatter. Data points falling closer to the lower line correspond to measurements made in a large open assembly facility, or measurements that used a technique that accounted for the gamma and neutron backscatter.

Figure 8  
Cassini Spacecraft Total Dose Rate Estimates  
Side, View (mrem/hr)



The model has been used extensively to produce 3-D analyses of spacecraft, instrument, and personnel radiation patterns. Figure 8 shows a side view of the Cassini spacecraft. Two of the three RTGs are visible cantilevered off the Lower Equipment Module ring near bottom of the figure. Dose rate contour lines in a plane through the centerline of the spacecraft provide estimates for personnel exposures after the RTGs are installed on the launch pad.

#### ACKNOWLEDGEMENTS

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#### REFERENCES

1. Los Alamos Document LA-7396-M, "MCNP - A General Monte Carlo Code for Neutron and Photon Transport," Version 4, (1990)
2. M. Taherzadeh, "Neutron Radiation Characteristics of Plutonium Dioxide Fuel," NASA Technical Report 32-1555 (1972)
3. P. Gingo and M. Dore, "Gamma Radiation Characteristics of Plutonium Dioxide Fuel," NASA Technical Report 32-1481 (1970)